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Galaxy Evolution in the Virgo Cluster

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Abstract. In the last years we have gained new insights on how ram pressure acts in detail on Virgo spiral galaxies. This has been possible due to the combination of new deep HI observations, deep polarized radio continuum observations, and detailed dynamical modelling (sticky particles and MHD). As a major result a first complete ram pressure stripping time sequence could be established for the Virgo cluster.

Keywords. Galaxies: clusters: individual: Virgo, galaxies: interactions, galaxies: ISM, galaxies: kinematics and dynamics

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1. Introduction

Nearby galaxy clusters represent natural laboratories to study environmental effects on the evolution of cluster galaxies. Since Gunn & Gott (1972) have introduced the concept of ram pressure stripping, which can affect galaxies moving rapidly inside the Intracluster Medium (ICM) of a galaxy cluster, this mechanism has been invoked to explain different observational phenomena such as the HI deficiency of spiral galaxies in clusters (Chamaraux *et al.* 1980, Bothun *et al.* 1982, Giovanelli & Haynes 1983) or the lower star formation activity of cluster spiral galaxies (e.g. Dressler *et al.* 1999, Poggianti *et al.* 1999). Whereas it is generally accepted that ram pressure stripping is responsible for the truncated HI and Hα disks in local clusters such as Virgo (Cayatte *et al.* 1990, Koopman *et al.* 2001) or Coma (Bravo-Alfaro *et al.* 2000), it is still an open question where and when these galaxies lose their gas and if a starburst can be triggered during the ISM-ICM interaction.

2. Ram pressure models

The ISM of a galaxy can be described in several ways: continuous description: Eulerian hydrodynamics in 2D (Rödiger & Hensler 2005) and 3D (Rödiger & Brüggen 2006), (Rödiger *et al.* 2006, Marcolini *et al.* 2003), discrete-continuous hybrid description: smoothed particles hydrodynamics: (Abadi *et al.* 1999, Schulz & Struck 2001), and discrete description: sticky particles (Vollmer *et al.* 2001). Only Vollmer *et al.* (2001) have used a time dependent ram pressure due to a radial galaxy orbit within the cluster.

The stripping mechanisms can be divided into two classes: classical momentum transfer stripping (Gunn & Gott 1972) with strong ram pressure where the typical interaction timescale is $\sim$ 10–100 Myr and turbulent/viscous stripping (Nulsen 1982) (constant low ram pressure) where the timescale is $\sim$ 1 Gyr. For turbulent stripping Eulerian hydrodynamic simulations are required. In the following only strong momentum transfer ram pressure stripping is discussed. Fig. 1 shows the resulting gas stripping radius as a function of maximum ram pressure for the different models. The end product of strong ram pressure stripping, i.e. a truncated gas disk, is the same for all models, but the time-dependent removal of mass and angular momentum might be different in these models.

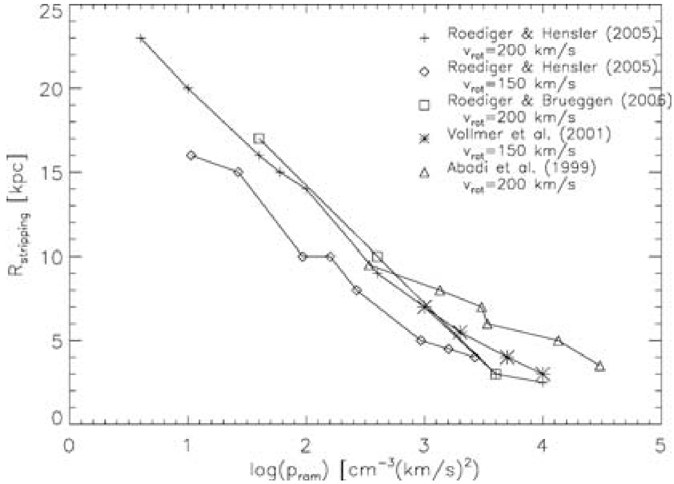

Figure 1. Comparison between different ram pressure stripping models.

3. Polarized radio continuum emission

Polarized radio continuum emission represents a diagnostic tool for interactions, which is complementary to interferometric HI data. Polarized radio continuum emission $S_{\rm PI}$ is proportional to the density of relativistic electrons $n_{\rm e}$ and the strength of the regular large scale magnetic field B to the power of $2-4$: $S_{\rm PI} \propto n_{\rm e} B^{2-4}$. Large scale means larger than the resolution of the observations which is about $20'' \simeq 1.6$ kpc for the VLA.

Whenever there is compression or shear the large scale magnetic field is enhanced and the polarized radio continuum emission increases rapidly. The total radio emission is sensitive to the turbulent small scale magnetic field which is usually a factor of 2.5–5 larger than the regular large scale magnetic field in spiral arms and 1.25–2 larger in the interarm regions. It is very difficult, if not impossible, to predict the distribution of polarized radio continuum emission on the basis of HI observations, because of the complex evolution of the magnetic field (induction equation) and beam depolarization effects. Therefore, it is necessary to make detailed MHD modelling for direct comparison with observations. In Otmianowska-Mazur & Vollmer (2003) we demonstrated the feasibility of the method and in Vollmer *et al.* (2004) we applied it successfully to the Virgo spiral galaxy NGC 4522.

Encouraged by our results on NGC 4522 we observed a sample of 8 bright Virgo spiral galaxies in polarized radio continuum emission at 20 cm (C array) and 6 cm (D array) at a spatial resolution of $\sim 20''$ (PI: B. Vollmer). The sensitivity at 6 cm is ~ 10 mJy/beam.

In a "normal" field spiral galaxy the polarized radio continuum emission is mainly found in regions between the spiral arms, because turbulence linked to star formation in the spiral arms destroys the large scale magnetic field. Only one observed galaxy, NGC 4321, out of 8 shows this characteristic distribution of polarized radio continuum emission (left panel of Fig. 2). All other galaxies show asymmetric distribution of polarized radio emission with ridges at the outer parts of the galactic disks. The middle and left panels of Fig. 2 show 2 examples for this kind of distribution.

The asymmetries are tracers of the interactions of Virgo spirals with their environment and can be used as diagnostic tools to determine the kind of interaction (gravitational or ram pressure) and the interaction parameters (Vollmer *et al.* 2004b, Soida *et al.* 2006).

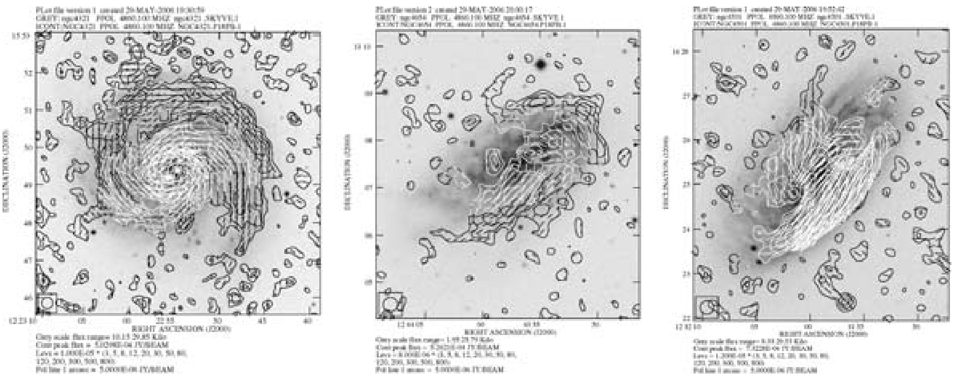

Figure 2. Three Virgo spiral galaxies observed in polarized radio continuum emission at 6 cm (contours). The magnetic field vectors are shown as lines. Greyscale: DSS image.

4. A first complete stripping sequence

Since the time to maximum stripping is determined by the comparison between the dynamical/MHD simulations and observations, we can establish a ram pressure time sequence once we have a large enough sample of galaxies.

For the direct comparison between model and observations for a given galaxy the known parameters are: the systemic velocity of the galaxy, its distance from the cluster center, inclination angle, position angle, gas distribution, and velocity field. With the help of the dynamical model we determine the maximum ram pressure, the time to the maximum ram pressure, and the angle between the galactic disk and the ram pressure wind. We have investigated 6 galaxies in detail (the results on NGC 4501 and NGC 4330 are preliminary).

This sample allows us to establish a first complete ram pressure stripping time sequence for Virgo spiral galaxies:

NGC 4501 and NGC 4330 are at the beginning of a ram pressure stripping event, i.e. they approach the cluster center. The outer disk has already been removed and the inner disk just begins to be affected by ram pressure.

NGC 4438 is approximately at its closest distance to the cluster center. Despite the strong tidal perturbation caused by its companion NGC 4435, ram pressure is the dominant effect on the gas distribution and kinematics (Vollmer *et al.* 2005). NGC 4522 is also close to peak ram pressure. However, this galaxy is located at a distance of about 1 Mpc from the cluster center. The most plausible scenario is that the intracluster medium is moving opposite to the galaxy's motion within the cluster (Kenney *et al.* 2004, Vollmer *et al.* 2006). This can enhance ram pressure significantly. The motion of the intracluster medium is most probably due to the infall of the M49 group of galaxies into the Virgo cluster from behind and from the south (see, e.g., Shibata *et al.* 2001).

After peak ram pressure, i.e when the galaxy leaves again the cluster core, the removed ISM is accelerated and expands. Thus extraplanar gas tail becomes larger and its gas surface density decreases. This is observed in NGC 4388 (Oosterloo & van Gorkom 2005) where the dynamical model yields a time to peak ram pressure of $\sim$ 100 Myr (Vollmer & Huchtmeier 2003).

If one then waits again for two galactic rotations ($\sim$ 200 Myr) the gas tail is no more detectable. The only traces of the past interaction are kinematically perturbed low gas surface density arms (Vollmer *et al.* 2004a). At the very end of this sequence stripped spiral galaxies show a truncated symmetric and unperturbed gas disk.

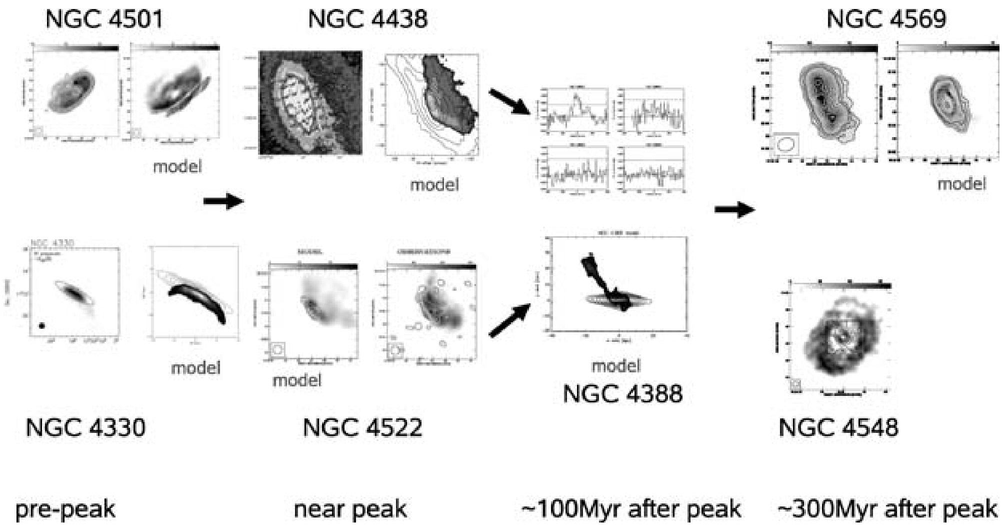

Figure 3. A first complete ram pressure stripping sequence in the Virgo cluster.

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Discussion

Curt Struck: The Gott and Gunn criterion was for gas removal from the disk with no halo. The fact that the scaling works suggests that gas removed from the disk is also removed from the halo, with little fallback, correct?

Bernd Vollmer: Yes, for the moment, there is no evidence of massive fallback onto stripped galactic disks. The only observational case where there might be fallback is NGC 4568, but it is far from being clear what happens to the ISM once it is pushed out of the galaxy.

Jan Palouš: Stripping differs in clusters with different ICM distributions but the same peak ram-pressure. This means that the Gunn & Gott's formula does not always work.

Bernd Vollmer: My statements are based on what we have learnt in the Virgo cluster. Your result surprises me and I would like to know the underlying reason why the Gunn & Gott's formula does not work.